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Suppression of the Transit –Time Instability in Large-Area Electron Beam Diodes*

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Abstract. Experiment, theory, and simulation have shown that large-area electron-beam diodes are susceptible to the transit-time instability. The instability modulates the electron beam spatially and temporally, producing a wide spread in electron energy and momentum distributions. The result is gross inefficiency in beam generation and propagation. Simulations indicate that a periodic, slotted cathode structure that is loaded with resistive elements may be used to eliminate the instability. Such a cathode has been fielded on one of the two opposing 60 cm x 200 cm diodes on the NIKE KrF laser at the Naval Research Laboratory. These diodes typically deliver 600 kV, 500 kA, 250 ns electron beams to the laser cell in an external magnetic field of 0.2 T. We conclude that the slotted cathode suppressed the transit-time instability such that the RF power was reduced by a factor of 9 and that electron transmission efficiency into the laser gas was improved by more than 50%.

INTRODUCTION

One promising design for a fusion power plant is based on using a modular array of intense krypton fluoride (KrF) lasers to directly compress and heat a small fuel pellet [1]. Such a KrF laser module would be pumped by repetitively pulsed, counter-streaming, large-area electron beams (e-beams). Theory, simulation, [2,3] and experiments [4] performed on the NIKE [5] KrF laser at the Naval Research Laboratory have shown that large-area, e-beam diodes are susceptible to the transit-time instability. The instability modulates the electron beam spatially and temporally, producing a wide spread in electron energy and momentum distributions. This results in inefficient and uneven pumping of the laser gas leading to spatial non-uniformities in the laser pulses. A transmission line analysis and 2-D MAGIC [6] simulations predict that a periodic, slotted cathode structure that is loaded with resistive elements may be used to eliminate the instability and improve efficiency [4]. The following sections investigate the transit time instability and report on the results of experiments

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14. ABSTRACT
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using a slotted/loaded cathode on NIKE. We conclude that the slotted cathode suppressed the transit-time instability such that the RF power was reduced by a factor of 9 and that electron transmission efficiency into the laser gas was improved by more than 50%. Experimental results and further 3-D Magic simulations indicate that a large-area diode can be designed that will eliminate the instability and meet the efficiency requirements for a power plant module.

TRANSIT-TIME INSTABILITY

A large-area, space charge limited diode can be modeled as a parallel-plate transmission line with distributed conductance and capacitance per unit length, G and C respectively. These parameters are functions of frequency f and the electron transit-time across the anode-cathode (AK) gap τ [2]. Whenever $\tau \approx (n+1/4)/f_n$ where n is an integer, the conductance becomes negative and a TEM wave supported by the gap will grow in amplitude [3]. Electrons emitted from the cathode experience the applied accelerating voltage modulated by the RF voltage from the TEM wave. The electrons alternatively give and receive energy from the field as they are accelerated and decelerated across the AK gap. When the frequency of the wave is such that the electrons give net energy to the field for the duration of their transition across the gap then the wave grows in amplitude and electron flow in the diode is unstable. For a 5 cm AK gap and a 500 kV voltage, the electron transit time is about 0.5 ns, $f_1 \approx 2.5$ GHz, and the predicted growth $\alpha \approx -3.9$ Np/m. Neglecting losses, the gain over a length of diode $l=2$ m is estimated at $e^{-\alpha l}=2440$. MAGIC simulations of the NIKE diode indicate that the instability has drastic effects on beam generation. A FFT of the simulated diode voltage waveform showed a high amplitude component at 2.5 GHz. The electron momentum distribution across the length of the diode was highly modulated showing the "imprint" of the wave. Moreover, an initially monochromatic 500 keV electron energy distribution had significantly spread from 250 to 750 keV, greatly reducing electron transport efficiency into the laser gas [4].

SUPPRESSION OF THE INSTABILITY

A transmission line analysis was used to design a diode to suppress the transit-time instability [4]. For the KrF laser application, a straightforward solution was to modify the cathode using periodic, resistively loaded, transmission line stubs that would impose a stop-band for the fundamental 2.5 GHz mode of the instability. This was accomplished by constructing a cathode from 3 cm wide vertical strips of emitter separated by 9 mm wide x 2.6 cm deep slots which were periodically loaded with a microwave absorbing material. For this design, G becomes positive at 2.5 GHz, the waves are attenuated, and the instability is suppressed. 2-D MAGIC simulations of this cathode showed 10^3 times less RF amplitude at 2.5 GHz on the diode voltage and no modulation of the electron momentum distribution while the electron energy distribution remained uniform at 500 keV [4]. Note that an additional advantage in

electron transport efficiency is gained when openings in the pressure foil support structure (hibachi) are designed to match the "stripped" beam pattern [7].

Figure 1 is a plan view of one side of the NIKE 60 cm aperture laser amplifier. For laser operations, counter-streaming electron beams are emitted from 200 x 60 cm^2 flat velvet cathodes that are immersed in an axial magnetic field of 0.2 T. The beams traverse a 5 cm vacuum AK gap, go through a 33 μm thick Ti anode foil, a 5 cm deep hibachi, and a 43 μm thick Ti pressure foil before entering the laser cell where they excite high pressure KrF gas to produce laser light at 248 nm. For the work discussed here, a single diode is used at 500 kV and a diagnostic plate/beam dump is placed at either the anode or pressure foil position. The diagnostic plate is covered with 1 cm thick carbon tiles and has several, centrally located, 5 cm diameter access ports for diagnostics. These include: i) a calorimeter which measured the average energy loss of electrons in a 50 μm thick Ti foil, ii) magnetic probes which measured dI/dt, and iii) an energy analyzer which consisted of an evacuated tube in which a beamlet propagated through 4 equally spaced, 140 μm thick, carbon foils with 5 Rogowski coils measuring the attenuation of the beam current after each foil. The average electron energy and a rough energy distribution were obtained by comparing the attenuated currents with results from MAGIC simulations. A magnetic probe outside the beam measured the RF noise; the total diode current and generator voltage were also monitored. A standard, flat velvet cathode and the slotted/loaded cathode with velvet strip emitters were compared.

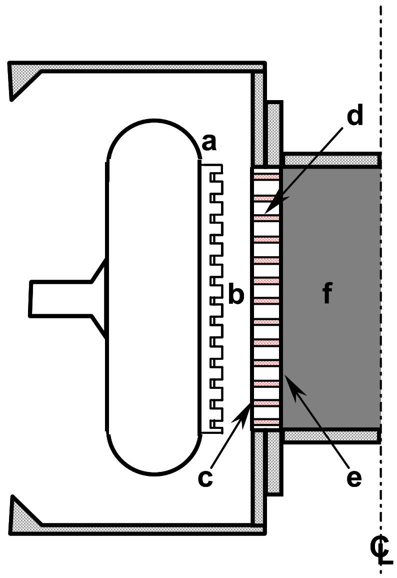

Figure 1. Drawing of NIKE diode: a) slotted cathode, b) AK gap, c) anode foil, d) hibachi, e) pressure foil, and f) laser cell.

Figure 2 illustrates the suppression of the instability. The time differentiated RF current in the flat cathode case shows early time, high amplitude oscillations. A FFT of the signal reveals high frequency components spread over 2-3 GHz range. The RF current in the slotted cathode case starts some 150 ns later and is significantly lower in amplitude with a narrow frequency spectrum near 2.2 GHz. When the two signals are corrected for cable attenuation, integrated, and squared, the slotted cathode case shows a factor of 9 reduction in RF power. Figure 3 shows the effect of the instability on the electron energy distribution. Energy analyzer data (•) taken at the pressure foil position with the flat cathode give attenuated currents that are comparable to those seen in simulations using an initial electron distribution that is a Gaussian of 400 keV average energy with a half-width of 150 keV (line A). The instability has caused a spread in electron energy which results in an average loss of ~50 kV/electron. With exacerbated losses in the pressure foil, the total electron transport efficiency was measured at 35%. Using the slotted cathode, the instability growth is reduced and the energy analyzer shows data (■) that closely resembles a 500 keV monochromatic

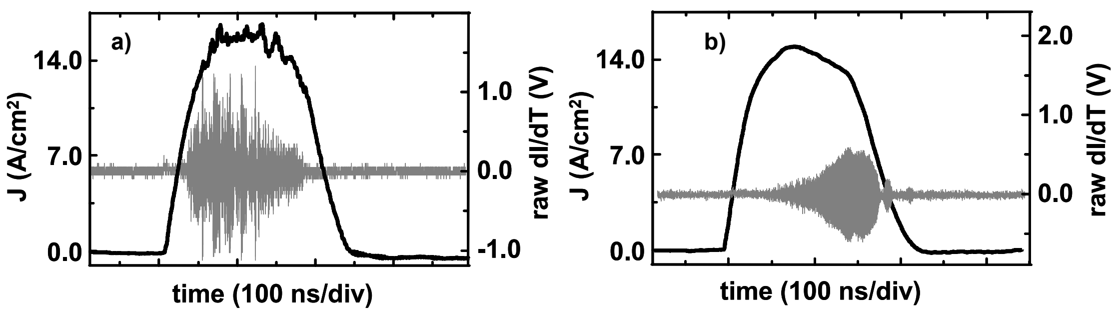

Figure 2. Time differentiated RF current superimposed on the beam current density profile measured at the pressure foil position for a a) flat cathode and b) slotted cathode.

distribution (line B). Suppression of the instability allows beam electrons to maintain their energy in the diode, reducing foil scattering and hibachi losses. The slotted cathode improved the total electron transport efficiency to 55%.

As designed, the slotted cathode suppressed but did not eliminate the transit-time instability. Although the gain is much smaller, it is possible that TEM modes may grow along the other, 60 cm dimension of the cathode. 3-D MAGIC simulations show that with a cathode slotted in both dimensions the instability is completely eliminated. Such a cathode design, used at the size and voltage required for a power plant module, is estimated to achieve an electron transport efficiency of 80%.

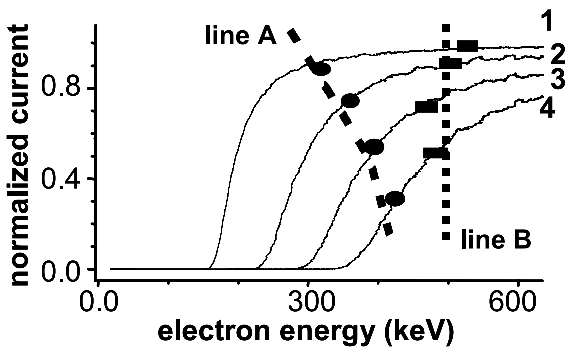

Figure 3. Calculated, normalized transmitted current through carbon foils 1-4 as a function of electron energy: line A- Gaussian electron distribution with average energy 400 keV and half-width 150 keV, line B- uniform 500 keV distribution. Energy analyzer data: •- pressure foil position with flat cathode; ■-anode foil position with slotted cathode.

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